Microstructural evolution of Ti-6Al-4V during high strain rate conditions of metal cutting

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Abstract

The microstructural evolution following metal cutting was investigated within the metal chips of Ti-6Al-4V. Metal cutting was used to impose a high strain rate on the order of ~10^5 s^{-1} within the primary shear zone as the metal was removed from the workpiece. The initial microstructure of the parent material (PM) was composed of a bi-modal microstructure with coarse prior β grains and equiaxed primary α located at the boundaries. After metal cutting, the microstructure of the metal chips showed coarsening of the equiaxed primary α grains and β lamellar. These metallographic findings suggest that the metal chips experienced high temperatures which remained below the β transus temperature.

Keyword: metal cutting, Ti-6Al-4V, grain refinement

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Outline

- Introduction
- Experimental Method
- Results
- Summary
- Future Works

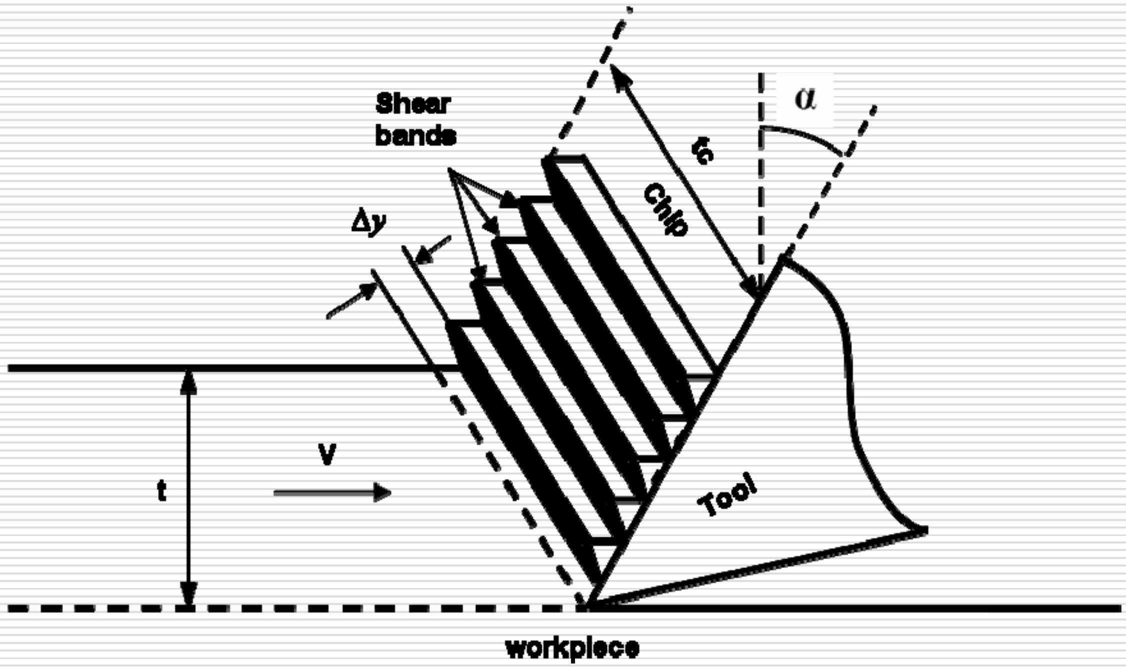
Objective

- Utilized metal-cutting to subject material to strain rates in the range of 10^3 to 10^5 s^{-1}
- Evaluated the microstructure response of Ti-6Al-4V to high strain rate conditions above 10^3 s^{-1}
- Investigated the response of the deformed microstructure to subsequent heat treatments

Ti-6Al-4V

- Titanium and its alloys has been widely applied in the aerospace, chemical, biomedical industry.
- Ti-6Al-4V is one of the most used titanium alloys.
- Young's Modulus:114 GPa; Ultimate Tensile Strength: 1170 MPa; Specific Heat Capacity: 0.5263 J/g-℃
- It is a two phase microstructure (α Ti **+** β Ti)
  - α Ti: hexagonal close-packed (hcp) structure
  - β Ti: body-centered cubic (bcc) structure
- Beta transus temperature: ~ 995℃

During metal-cutting, the metal removed experiences a localized high shear strain rate



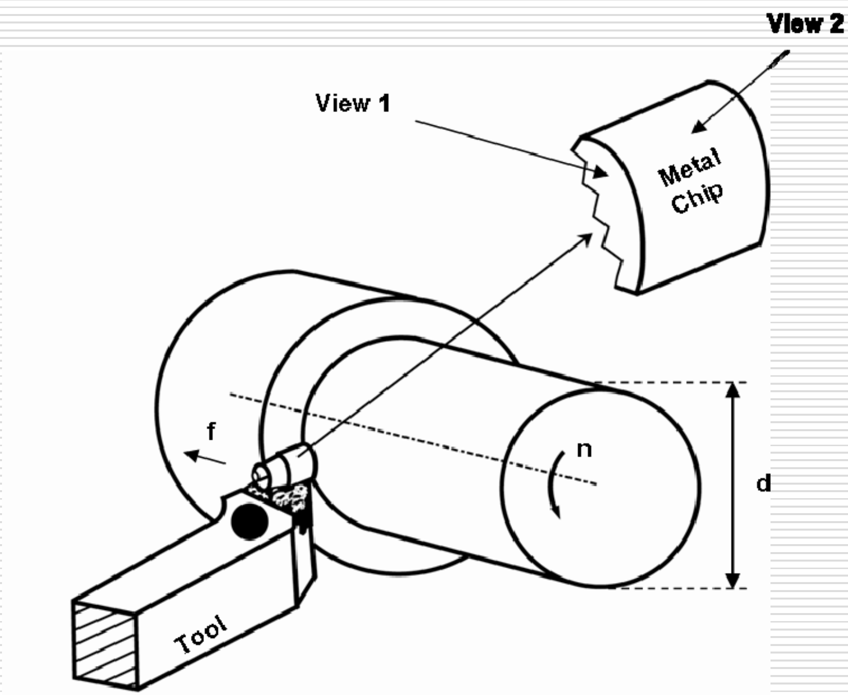
Classic orthogonal metal-cutting schematic

$$\gamma = \frac{\cos\alpha}{\sin\phi \cdot \cos(\phi-\alpha)}$$

$$\dot{\gamma} = \frac{\cos\alpha}{\cos(\phi-\alpha)} \cdot \frac{V}{\Delta y}$$

$$\tan\phi = \frac{\frac{t}{t_c}\cos\alpha}{1-\frac{t}{t_c}\sin\alpha}$$

A turning process can used to approximate orthogonal cutting conditions



Cutting parameters:

Rake angle : +5°

Depth of cut : 360μm

Travel velocity : 0.22 ~ 0.57 m/s

Estimated shear strain rate :

1~ 2 ×10^5 s^{-1}

Estimated shear strain: ~ 5

Schematic of turning operation with chip morphology

Heat Treatment Schedule

- Heat treat as-cut metal chips at 260°C and 730°C for 5, 15, 30 and 90 minutes, respectively.
- 260°C was selected to study the low temperature microstructural response.
- 730°C was selected as the beginning temperature range of the α to β phase transformation.

Metallurgical Study

- Cut metal chips were characterized using variety of characterization techniques.

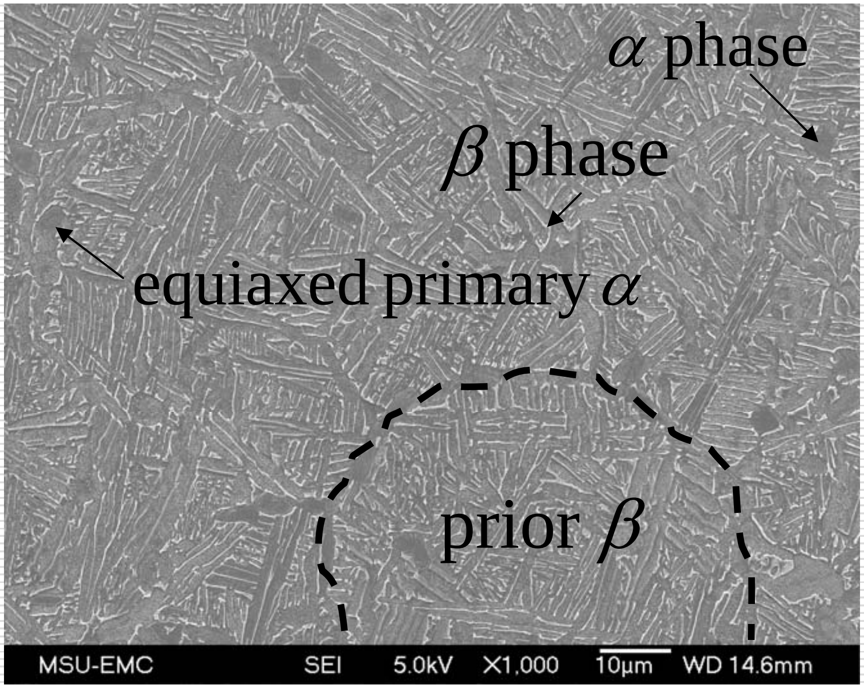
Metal-cutting chips

→ **Scanning Electron Microscopy (SEM)**
Phase content and morphology

→ **Transmission Electron Microscopy (TEM)**
Submicron microstructure

→ **X-ray Diffraction (XRD)**
Phase content and Texture

As-received parent material shows a bi-modal microstructure



width of α laths: 1.0 μm

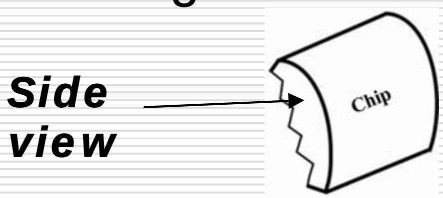
equiaxed primary α: 5.2 μm

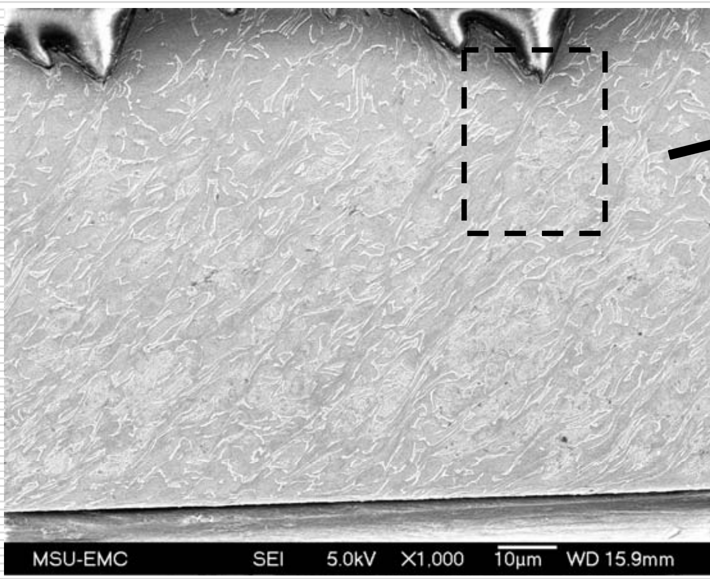
prior β: 50 μm

volume fraction of β phase: 12 ~ 13%

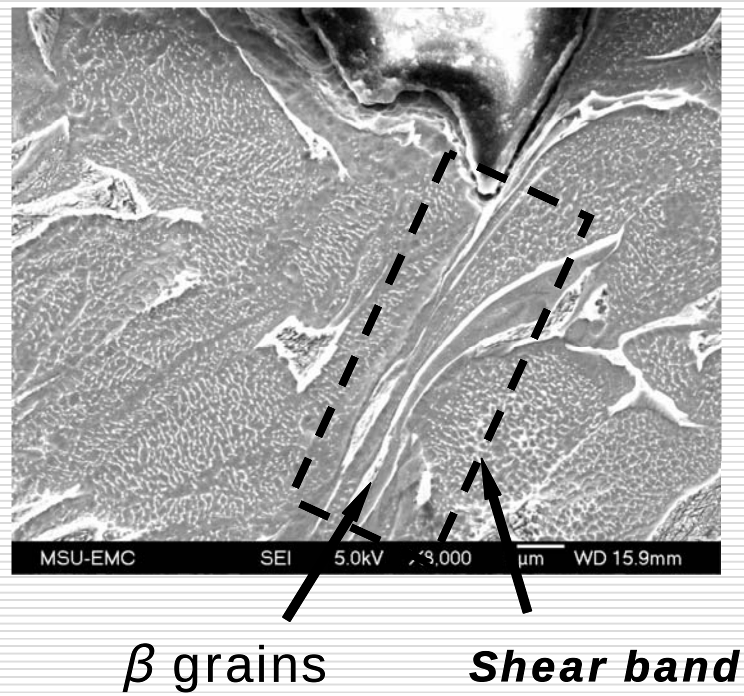
Evidence of non-homogenous shear bands observed in side view

- SEM images



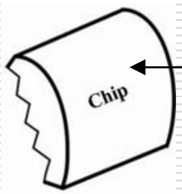


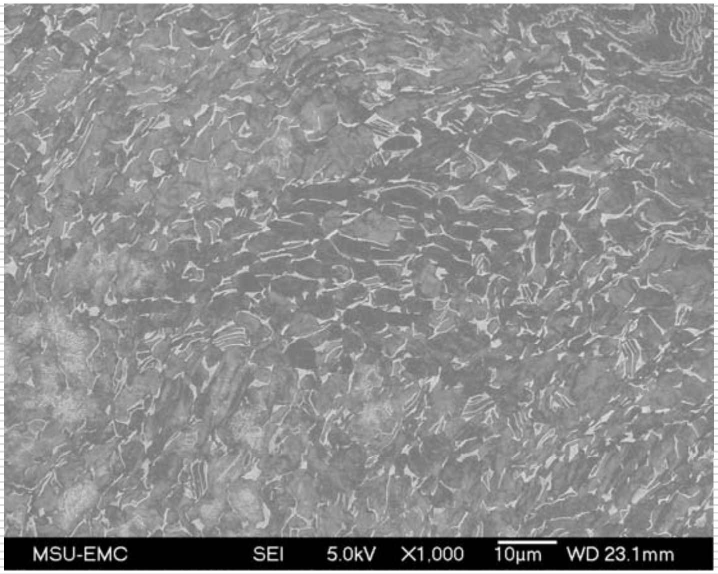
$1.9 \times 10^5\ s^{-1}$



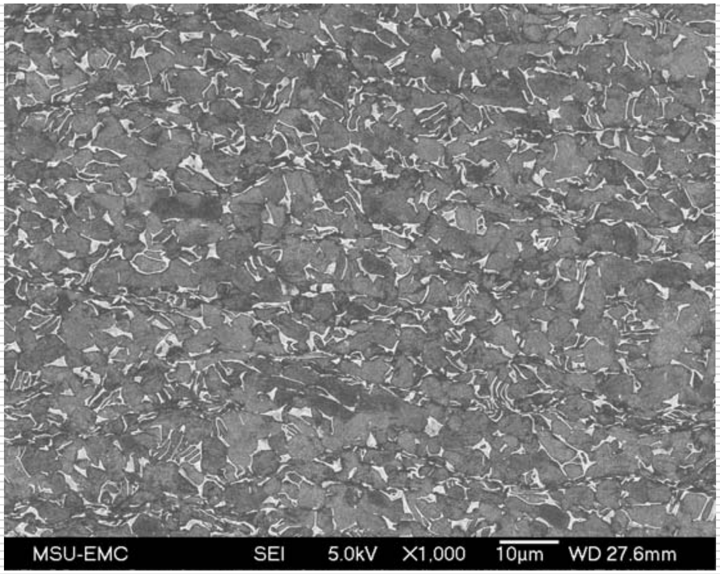
No change in grain size observed on cutting surface

- SEM images





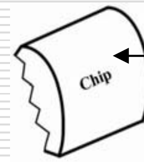
$1.1 \times 10^{5}\ s^{-1}$



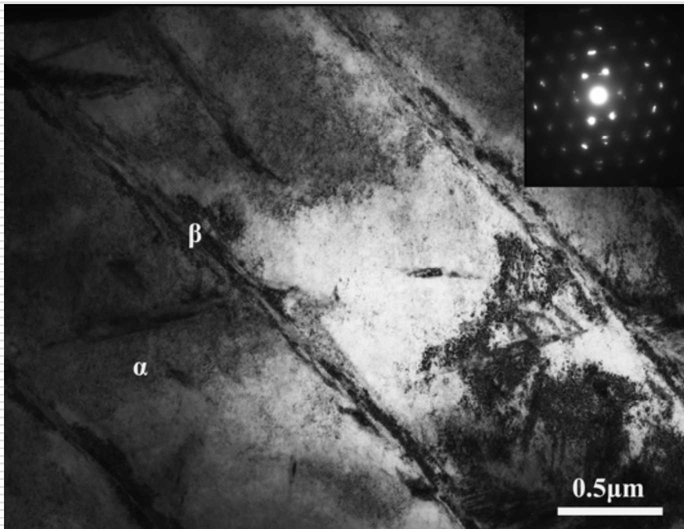
$1.9 \times 10^{5}\ s^{-1}$

Equiaxed α grain = 4.8 ~ 5.1 μm

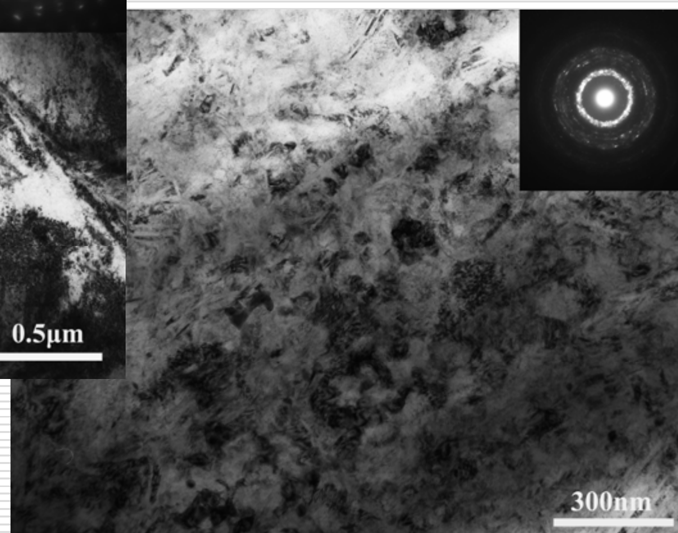
Evidence of nano-crystalline microstructure observed in TEM/SAD



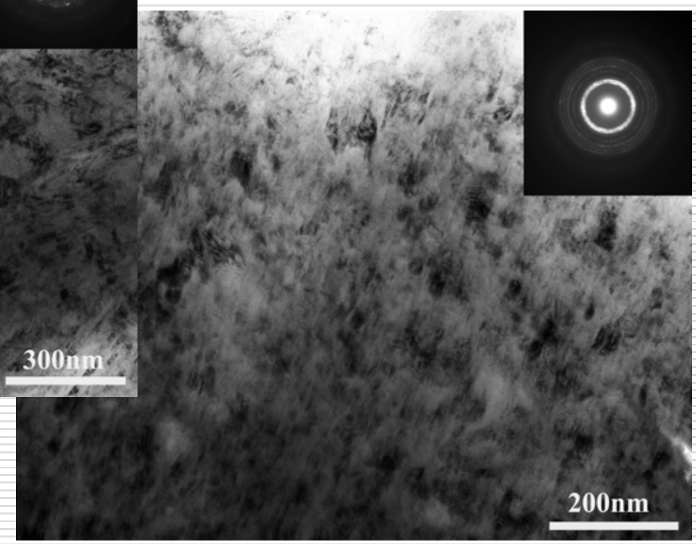
Cutting surface



PM

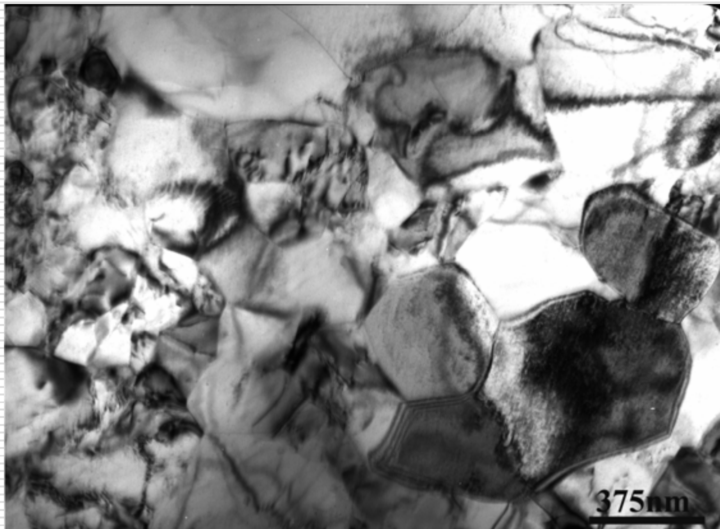


1.1×10^5 s^{-1}

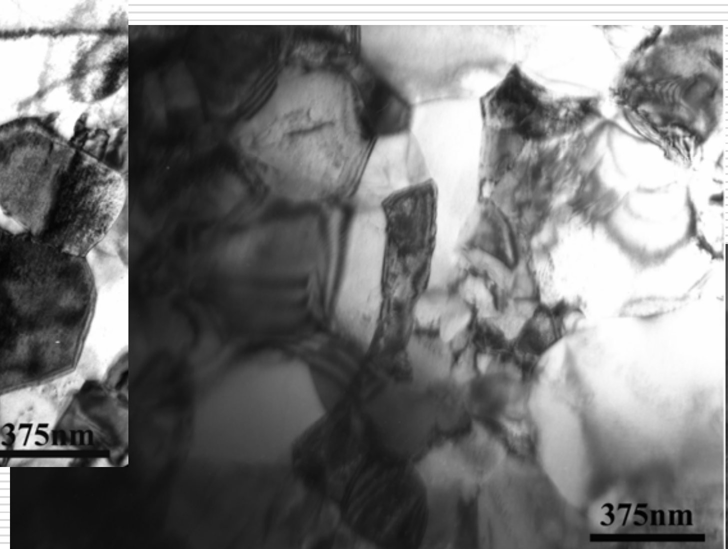


1.9×10^5 s^{-1}

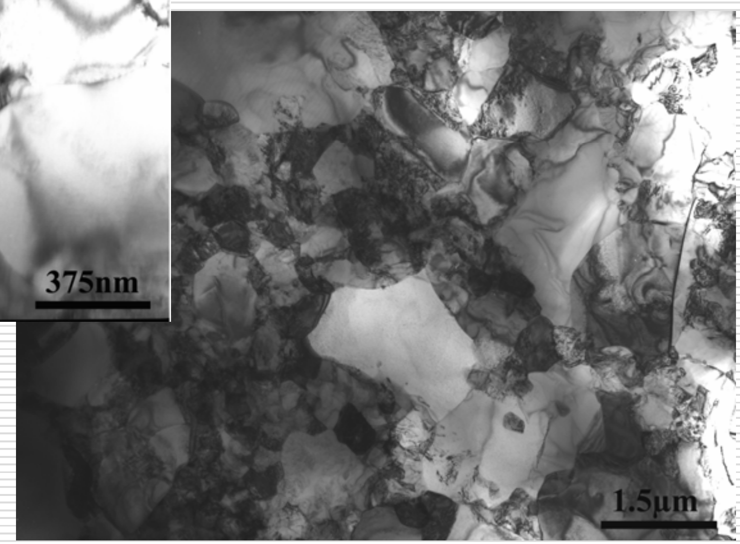
TEM micrograph of heat treated metal-cutting chips



5 min



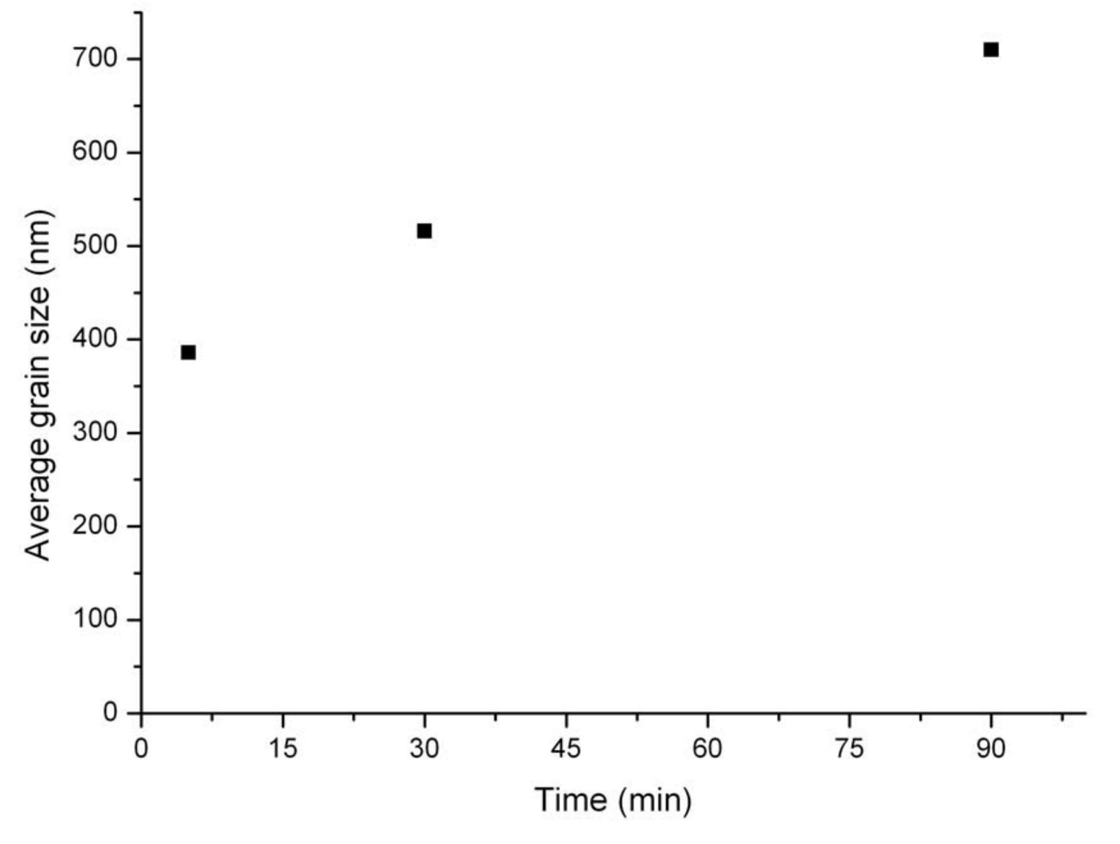
30 min



Heat treated at 730℃

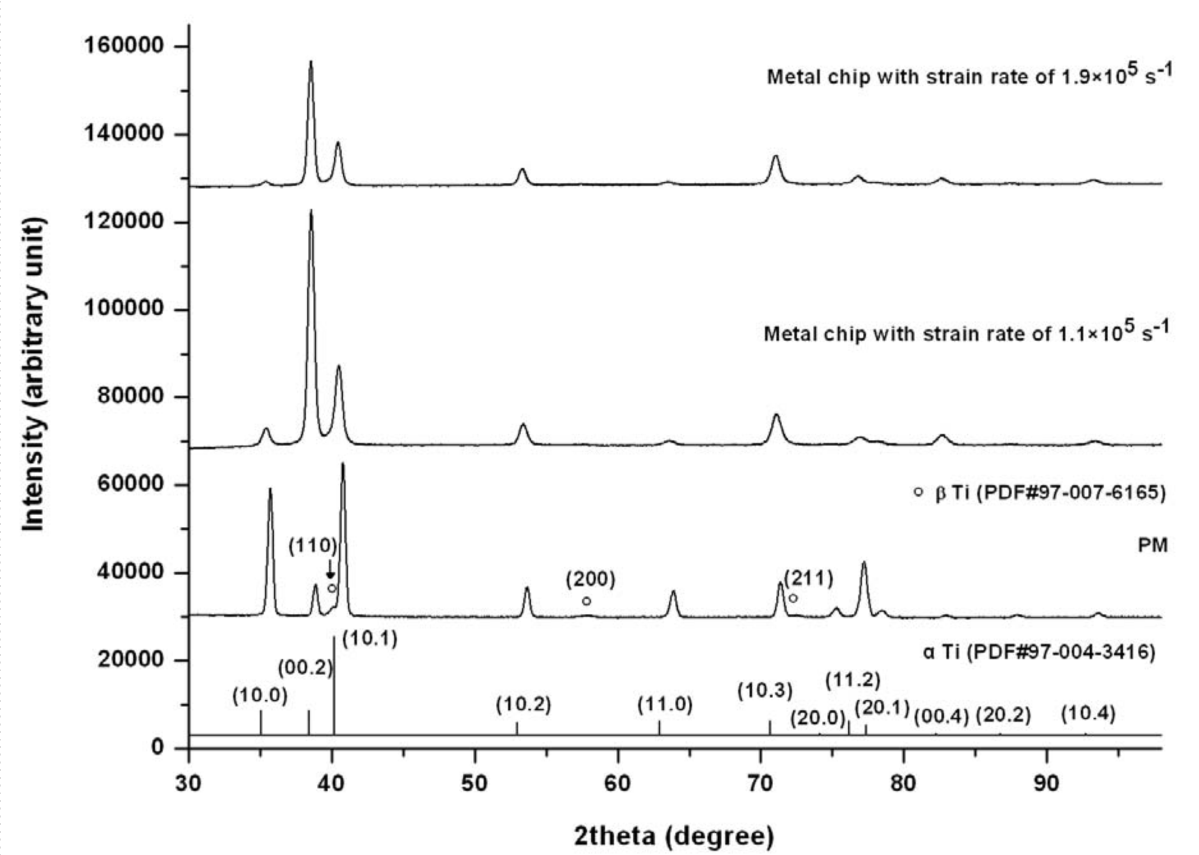
90 min

Grain growth rate of α phase



Heat treated at 730℃

A change in rolling texture of the α phase is observed after the metal cutting process



XRD Summary shows minor peak broadening

hkl	***PDF#*** ***97-004-3416***	PM		strain rate = 1.1×10^5 s^{-1}		strain rate = 1.9×10^5 s^{-1}	
			FWHM		**FWHM**		**FWHM**
(10.0)	**35.089**	**35.691**	**0.357**	**35.320**	**0.533**	**35.285**	**0.501**
(00.2)	**38.449**	**38.842**	**0.337**	**38.534**	**0.465**	**38.510**	**0.426**
(10.1)	**40.178**	**40.771**	**0.366**	**40.447**	**0.564**	**40.402**	**0.502**

Summary

- Microstructure observation shows an evolution from initial bi-modal microstructure to equiaxed α grains with intergranular β grains.
- The resulting microstructure suggests that the β transus was not exceeded during the metal cutting.
- Microstructural analysis indicates a non-homogenous grain refinement has occurred within the shear band region.
- The heat treatment experiment indicated the formation of nano-crystalline and refined grains have good thermo-stability up to 730°C

Acknowledgements

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